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Principal Investigator: Germanovich, Leonid N. **Award ID:** 0609950
Organization: Georgia Tech Research Corp
Submitted By:
Germanovich, Leonid - Principal Investigator
Title:
Collaborative Research: Characterization of Fractured Rock Aquifers Using Hydromechanical Well Tests

Project Participants

Senior Personnel

Name: Germanovich, Leonid
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Song, Xiaoyu
Worked for more than 160 Hours: Yes
Contribution to Project:

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Clemson University

Other Collaborators or Contacts

Larry Murdoch, Clemson University

Activities and Findings

Research and Education Activities:
Research activities consist of advancing experimental equipment and theoretical analyses used to conduct and evaluate hydromechanical well tests.

2007 - 2008

Apparatus

Significant progress has been made on the development of a multi-axis extensometer, a major objective of the project. We have evaluated a variety of approaches and the most viable technique available to us now is to combine a borehole tiltmeter with an extensometer. The borehole tiltmeter called LILY by Applied Geomechanics has the performance specifications to measure deformations on the same scale as those detectable by our extensometer technology. LILY has nano-radian resolution, which is the finest currently available, and it has a built in self-leveling mechanism, which enables the device to be mounted up to 10 deg off level. Clemson's group purchased a LILY tiltmeter for evaluation. The device is housed in a cylindrical shell designed to be cemented into a boring. This configuration is incompatible with our approach, which requires the device to be temporarily mounted to the borehole.

We designed and fabricated a prototype frame for mounting the LILY tiltmeter in a borehole. This device was successfully tested to demonstrate proof-of-concept in April. The design is based on the opposing anchor system we developed for the extensometer. Initial testing demonstrated that this approach was viable for temporarily deploying a high resolution tiltmeter in a borehole. However, the preliminary results indicated a drift that we suspect resulted from the design of the anchors. We are currently fabricating a spring-based anchor system for the LILY tool to evaluate the extent to which it will reduce drift.

Upon completion of the proof-of-concept testing of the LILY downhole tool, we initiated the construction of a prototype system that combines the tiltmeter with our extensometer technology. We have developed a detailed design for this new device and the prototype is in the machine shop now. We plan to test the device this summer. To our knowledge, this will be the first multi-axis, portable device with nearly nano-scale (10-8) resolution of tilt and axial strain.
The current extensometer was refined further over the past year. We implemented the 24-bit downhole system with both the LVDT and DVRT.

We plan to measure Earth tides in August. Since November, we have rebuilt the downhole electronics and changed the LVDT. We have also refined the DVRT measurement system. We are optimistic that these changes will enable us to further increase precision in order to detect displacements due to Earth tides with the existing system.
We have pursued developing our own data acquisition systems in house, and Dave Hisz in particular has made significant progress. Our entire field system is now run by several custom LabView software packages.

FIELD APPLICATIONS

We successfully mobilized the extensometer system from Clemson to New Jersey, deployed the system in the field, made some excellent measurements, and returned. This was the first time we had worked at another site, and this was an important milestone because it demonstrated that the technique was fully mobile. We expect that this will open the door to applications at many locations.
The field test was conducted at the NAWC site, a facility that has been used for research by the USGS for many years. We tested two wells in an uncontaminated area of the site, and the results we significant in several ways. The data was the highest quality we have produced yet, with a noise level of +/-25nm, and this was particularly gratifying because we were able to accomplish it after mobilization.

The most significant aspect of the data, however, is that it has led to several insights that could be important discoveries about the hydromechanical performance of aquifers. This glowing report of the data is in sharp contrast to our opinions in the field. The behavior at one of the boreholes was completely opposite from what we have seen in the past?fractures closed in response to increasing pressure and opened in response to decreasing pressure. When this happened in the field we were certain that it was a mistake. However, the equipment was thoroughly checked and we are confident that the results are valid. The other problem we had occurred when we tried to analyze the data from the other well using our existing model. It was impossible to fit the data.

The behavior of both tests at the site can be explained by expanding our theoretical analysis to include poro-elastic matrix in addition to deformation discrete fractures. It was the interaction between the poro-elastic effects in the matrix and the deformation fractures that caused the peculiar responses. It is possible to close a fracture by pressurizing a well bore, for example, by pressurizing the matrix. This causes the matrix to expand, closing the fracture. Our parameter estimate exercise required that a second fracture be present to get the required fit, and there was field evidence that a second fracture existed.

We were also able to fit the data from the other well, but here the analysis indicated that there must be a vertical crossing fracture to get the observed response. Indeed, a geophysics study published several years ago also concluded that there must be vertical fracture near the well, and this study was only pointed out to us after the analysis was complete.

These results indicate that we need to move to more complicated poro-elastic analyses to explain the results of our field tests.

THEORETICAL ANALYSES

A significant step forward in our theoretical analyses came with the implementation of Comsol Multiphysics analyses for poro-elastic calculations of well tests. This technique was implemented in 2-D and 3-D, significantly advancing the types of analyses we could conduct. This approach was key to explaining our field data for example.

Another exciting development has been the application of advanced parameter estimation technique using Markov chain Monte Carlo techniques to interpret hydromechanical well tests. These techniques were implemented and we demonstrated that they worked. However, they were quite slow. We recently have implemented them on a parallel computer and this is showing some encouraging results. To my knowledge, this project is supporting the first of this type of inversion technique used to study poro-elastic problems in ground water hydrology.

We have continued to pursue analyses showing the meaning of specific storage in aquifer tests. We developed a new closed form analytical solution that confirms our earlier analyses showing that specific storage is a response of pumping, and not an aquifer property. We have been reluctant to publish this finding because it will be controversial, but with the new analytical solution to compliment our numerical and field data we feel that we can now make a solid case.
We have also initiated work on an analytical solution for the poroelastic response of a slug test. This would be directly applicable to our field studies. This analysis could lead to type curves for poro-elastic analyses of slug tests, which would parallel the often cited Cooper, Bredehoeft, Papadapolous solution for slug tests in a confined aquifer. This would be a significant step forward. Preliminary work suggests that the analysis is feasible, but additional work is required before it is available.

2009 - 2010

Apparatus

The development of a combined tiltmeter-extensometer device progressed through this fiscal year. We call this device 'Tilt-X' and activities include a program of design, testing and refinement. We developed a working prototype of the device over the fall, with a proof-of-concept field deployment in late fall and winter. The deployment took place at Clemson's well field and consisted of evaluations of the instrument during well testing and during ambient conditions.

The initial deployment also demonstrated the need for a refined registration system for Tilt-X. The registration system moves the device to the mid-range of the stroke of the displacement sensor. The high resolution sensor that we are using in Tilt-X has a small stroke (+/-250 microns) and the proof-of-concept tests demonstrated that the device can move considerably during deployment, which causes the sensor to be off-scale when a test is conducted. The original Tilt-X included a passive registration system, and the performance of this system indicates that revisions in the design would be helpful.
A new active registration system has been designed and constructed for Tilt-X using principles developed for the registration system on our previous extensometers. The Tilt-X with the active registration system performs well in the lab and we are currently preparing for field tests.

Field Tests

We mobilized the borehole tiltmeter and extensometer system and conducted tests at an experimental field site in Virginia operated by Tom Burbey at Virginia Tech. This test represented our first mobilization of the tiltmeter system and represented a test of the robustness of the instrumentation and data acquisition equipment.
The Virginia site was selected because it is underlain by a dipping fracture, according to previous work done by Tom Burbey and his students. We wanted to test a site with a known dipping fracture because understanding the effects of fracture dip on displacement is one of the primary motivations for using the tiltmeter.

The test occurred in mid-August, 2009, and we conducted pumping tests for 4 days. The instrumentation functioned well, and essentially this effort proved that downhole, moveable tiltmeters could be used during aquifer pumping tests.

Some aspects of the results of the tests were as we expected. The borehole deformed by tilting in an up-dip direction. A tiltmeter near the outcrop of the fault tilted in the down-dip direction, and extensometers showed both compressive and extension strains at different locations. All of those responses are consistent with theoretical findings.

Repeated pumping tests showed that the magnitude of the tilt at the borehole decreased with each test. This response is not predicted with basic theoretical analyses. However, this borehole was hydraulically fractured, and ours were the first well tests to be conducted since the hydraulic fracture was created. We suspect that the decrease in the response of the tilt signal may have been caused by the seating of asperities on the surface of hydraulic fracture. This process seems reasonable and would have important implications to hydraulic fractures in crystalline rock.

Another field deployment was conducted in late fall through early winter. This deployment involved the Tilt-X device, a system capable of measuring both tilt and displacement of aquifers. The proof-of-concept deployment demonstrated that the Tilt-X device functioned remarkably well. Noise levels on the scale of several minutes were in the +/-5 nm range for the extensometer and +/- 30 nrad for the tiltmeter. Both systems showed a large signal to noise response during modest pumping tests during the deployment, which we consider a successful proof of concept.

Theoretical Analysis

We have developed fully coupled, hydromechanical analyses of well tests involving dipping fractures. This was done using Comsol Multiphysics. Results were used first to plan, and later to analyze the Virginia field tests. The analysis is functioning correctly and provides useful results for forward simulations. We are also pursuing methods for reformulating the analysis of a dipping fracture in order to make it run faster. This work is ongoing.

Another analysis that is being pursued is a more general evaluation of poroelastic deformation during pumping tests in heterogeneous systems. This type of analysis highlights deformation that occurs during well tests and it is being conducted to evaluate the feasibility of identifying heterogeneities using hydromechanical measurements.

2011

In 2011, we mainly focused on advancing theoretical analyses used to conduct and evaluate hydromechanical well tests.

We have continued to pursue analyses showing the meaning of specific storage in aquifer tests. During the work on this project, we developed a new closed-form analytical solution that confirms our earlier analyses showing that specific storage is a response of pumping, and not an aquifer property. Previously, we had been reluctant to publish these findings because it would be controversial, but with the new analytical solution to complement our numerical and field data we feel that we can now make a solid case. Accordingly, we spent considerable time in refining both our analytical solutions and numerical techniques.

The numerical technique now includes fully coupled poroelasticity, which allows more realistic modeling of deformable aquifers and fractures. The obtained solutions are compared with our field data, which would be difficult to understand without this numerical treatment.

Significant effort was spent developing mathematical justifications of the closed-form solutions. Because we use these solutions both for gaining basic understanding and as benchmark problems for our numerical codes, we wanted to make sure that the solutions are sufficiently rigorous from the mathematical standpoint.

As originally proposed, we studied natural fractures in the subsurface that are held open by stresses on contacting asperities and by fluid pressure in their open space. Changing the fluid pressure shifts the stresses on the asperities and may cause a net change in the total stress on the fracture surface. Changes in the total stress result in normal displacement of the walls of the fracture. For simplicity, we ignored shear displacements and assumed that normal displacement of the fracture satisfies both local and global constraints, defined in our previous work [Murdoch and Germanovich, 2006]. Specifically, we assumed that local normal displacements are proportional to changes in effective stress with parameters determined from known laboratory experiments, which is adequate for the ranges of stress change caused by most pumping tests.

On the other hand, displacement of the fracture walls at a particular location may be caused by changes in total stress anywhere on the fracture surface. This non-local effect can be visualized by conceptualizing the fracture walls as a half-space. A point load will indent the half-space over a region beyond the location of the load. Displacement caused by a distributed load can be represented by integrating the response from point loads over the half space.

Following this conceptual model, we represented these non-local displacements and used known expressions for the displacements of the half-space surface caused by an axially symmetric distribution of total stress. Local and non-local displacements must be equal, so we equated them to obtain an equation for the normal displacement expressed as a function of time and coordinate.

We then considered the compressibility in the vicinity of a well in a thin, uniform layer shaped like a circular disk. Many fractures are conceptualized as circular disks, and some aquifers or reservoirs are roughly circular and bounded by relatively low permeability materials, so the circular shape provides a reasonable representation of at least two natural conditions. We employed the well-known expression for the pressure distribution caused by a constant line source along the axis of a disk of radius. As a result we obtained a non-homogeneous Fredholm integral equation of the second kind with respect to the unknown function (distribution of fracture compressibility and storativity in the fracture).

We proved that the kernel of this equation is square integrable, and, therefore, the equation has a solution. Furthermore, we identified a dimensionless parameter that controls this solution, and analyzed in detail its asymptotic behavior when the parameter is relatively small. The parameter basically represents the relative rigidity of the fracture with respect to the host rock, so our solution covers the case when the fracture is 'softer' than the rock.

We found the solution in the form of the Neumann series, and using the Banah fixed point theorem, we identified the exact range of the small parameter when the obtained series converges.

We further showed that for this range of the small parameter the series converges rapidly, and showed that the error of the truncated series does not exceed the first omitted term. This allowed us to keep only the first term to define the compressibility, and to control the error of the actual computations based on the obtained closed-form solution.

Because the findings from the analytical solution identify fundamental behaviors of compressibility and normalized storage, we are now quite comfortable in publishing these results. The paper preparation is in the final stage and we plan to submit it in August or early in September. The paper draft is attached to this report.

We also started the analysis of another limiting case when the parameter is relatively large. This is probably less realistic for a deformable fracture, but will be useful to represent some cases of relatively rigid aquifers.

2012

FIELD APPLICATIONS

In 2012, we participated in the field test conducted at the NAWC site, a facility that has been used for research by the USGS for many years. We tested three wells in an uncontaminated area of the site and mobilized the borehole tiltmeter and extensometer systems.. The data still needs to be processed and analyzed, but we expect it to be of high quality. This is particularly gratifying because we were able to accomplish it with new and recently modified instruments.

THEORETICAL ANALYSIS

We continued the analysis of the limiting case of a relatively large dimensionless parameter characterizing material properties in our study of the storage properties. Initially, we thought that this was probably less realistic for a deformable fracture, but could be useful to represent some cases of relatively rigid aquifers. Comparison with COMSOL numerical computations and field data showed, however, that this case may be quite representative. Implementation of Comsol Multiphysics analyses for poro-elastic calculations of well tests is a significant step forward in our theoretical analyses. This technique was implemented in2-D and 3-D, significantly advancing the types of analyses we could conduct. This approach was key to explaining our field data for example.

Another exciting development has been the application of advanced parameter estimation technique using Markov chain Monte Carlo techniques to interpret hydromechanical well tests. These techniques were implemented and we demonstrated that they worked. However, they were quite slow. We recently have implemented them on a parallel computer and this is showing some encouraging results. To our knowledge, this is the first of this type of inversion technique used to study poro-elastic problems in ground water hydrology.

Findings:

This project has contributed to the understanding of fundamental aquifer mechanics by developing innovative instrumentation, theoretical analyses and field techniques.

I. Instrumentation

Downhole tiltmeter. This portable device allows high-resolution tilts to be measured in fractured rock. Similar devices have been used in the petroleum industry, but they are unavailable commercially and have never been applied to aquifers, where previous applications of tiltmeters have required semi-permanent installations that are costly and cumbersome. This innovation should facilitate the use of borehole tiltmeters in hydrology.

Tiltmeter-extensometer. This device is capable of measuring tilt and axial deformation at the same location. To our knowledge, a device with these capabilities has never been described. This device allows local axial deformations to be measured along with local shear or rigid rotation. The device enables measurements of tilt and displacement during ambient and pumped conditions that have not been described previously.

3D-extensometer. This device measures both axial (vertical) and both horizontal components of deformation. It uses fiber optic sensors that are immune to interference and can be multiplexed on a single fiber to facilitate field deployment. The device is remarkably simple and compact, so further refinement should result in a technology that can fully characterize local deformations. A refinement of the current prototype should enable 5 degrees of freedom to be measured.

Sensors. DVRT sensors can provide even higher resolution data than previously realized; recent applications show an RMS noise level of 1.4 nm at 1 Hz. Field applications have also shown that this device is vulnerable to interference that markedly increases the noise by several orders of magnitude. In one case, this interference was caused by another DVRT over 20m away. Fiber Bragg Grating (FBG) sensors using optical fibers appear to be a viable alternative to DVRTs. They are immune to EM interference. Noise level of FBGs is expected to be on the order of 10 to 20 nm at 1 Hz, although these sensors can be sampled at high frequency to improve resolution.

II. Theoretical analysis

Analytical. A new closed form solution to the pressure and displacement in a layer intersected by a pumping well was derived. The analysis shows that the compressibility of a layer varies with time and space, and it also shows how the pressure and displacement evolve during pumping. This analysis is a significant advance from currently available closed-form solutions.

Numerical. Finite element analyses of the deformation during well tests were developed using Comsol Multiphysics. This approach was used to explain field observations. This code is readily available and our work describes how other investigators could use it for similar applications.

III. Field Techniques

Ambient conditions. The instrumentation outlined above was used to measure deformation resulting from Earth tides and barometric fluctuations.

Well tests. Field techniques were developed to deploy and evaluate measurements of 3D deformation and tilt during pumping and slug tests.

IV. Insights into Aquifer Mechanics

Specific storage. Specific storage is regarded as a material property in conventional groundwater hydrology, but we have field and theoretical evidence showing that it varies with both space and time during a well test. This finding shows that storage change is a variable response that cannot be characterized by the material property specific storage.

Matrix deformation. Injection causes fractures to dilate, but the matrix adjacent to the fractures is compressed. This occurs as a response to the loading within the fracture.

Reverse water level fluctuations. Fluid pressures increase in much of a fracture during injection, but they decrease at the leading edge of the zone affected by the well. This occurs because the dilation of the fracture walls occurs beyond the leading edge of the pressure front created by injection. This effect is related to the reverse water level responses known as the Noordbergum and Rhade effects, but it differs fundamentally from those known responses because it occurs within a hydraulically active fracture instead of within a confining unit.

Integrated aquifer characterization. Data from hydromechanical well tests can be integrated with water level changes due to barometric effects and Earth tides to characterize fractured rock aquifers. This approach appears to give more reliable results than conventional methods. Application of these techniques at a well that was hydraulically fractured shows that the compliance of the fracture decreases with each pumping test, presumably because asperities on the fracture face slip slightly and become better seated during each test.

Dipping fracture zones. Deformation that occurs during pumping can be characterized with both extensometers and tiltmeters. Tiltmeters allow rigid body rotation to be measured, whereas this effect cannot be detected by extensometers. Tilt signals can be interpreted using theoretical analyses to improve estimates of permeability distribution. An example field test conducted at Clemson shows a response that can be explained by an underlying fracture zone that is inclined, and the results of the test can be interpreted to yield the orientation of the fracture zone. Future applications of combined tiltmeters and extensometers should yield improved estimates of the structure of fracture zones.

Findings by project year are summarized below

2007

1. Storativity and Transmissivity change as functions of time and drawdown as a result of hydromechanical deformation during a pumping or well test.

2. Storativity increases with time as a result of the evolving pressure perturbation caused by pumping. Early in the pumping history, storativity is related to the elastic modulus and characteristic length of fractures, whereas late in a well test the storativity is related to the normal stiffness of the fractures. Storativity changes by factors of 5 to 10 or more during both field tests and theoretical analysis.

3. It appears that Storativity is not a meaningful aquifer parameter because it changes with time in response to a transient pressure field.

4. Transmissivity changes as fracture apertures respond to drawdown. This causes the transmissivity determined during a well test to be a function of the average drawdown (or build up) created by the test. As a result, slug-in tests predict large T than slug-out tests do.

5. Transmissivity can change by significant amounts when wells are highly stressed by significant drawdowns. This effect may be responsible for significant reductions in well performance (it can cut the performance in half or less). This effect will resemble skin or damage caused by drilling.

2008

1. Reverse water-level changes occur early in interference slug tests. Reverse water level changes in confining units, the so-called Noordbergum effect, are widely known to accompany pumping tests, but to our knowledge, this is the first time this effect has been reported during slug tests. We have field evidence and can explain this effect theoretically, and it appears that this effect probably accompanies all slug tests in fractured rock. We expect that it has not been reported before because it is relatively fast (it could be missed or ignored), and it requires using a packer in the monitoring well.

2. Reverse water-level changes during interference slug tests are sensitive to aquifer parameters and can be interpreted to characterize aquifers. Elastic modulus, fracture normal stiffness and aperture all have unique signatures during the reverse water-level change.

3. A line search algorithm appears to provide a mechanism for optimizing the number of packer tests required to characterize the heterogeneous architecture of a fractured aquifer.

4. Turbulence reduces well performance in much the same way that fracture deformation does. The head losses caused by turbulence increase the closure caused by deformation, so these two processes are coupled to reduce the performance of wells.

2009

1. The equipment required for hydromechanical well tests can be mobilized and deployed. This technique appears to be technically feasible to conduct in most hydrogeologic settings.

2. We successfully measured hydromechanical response in clastic sedimentary rocks.

3. The hydromechanical response of fractured sedimentary rocks involves a coupling between the fractures and the matrix. Hydraulic properties of the fractures control the well bore pressure. Both the fracture and matrix control the displacement. Low hydraulic diffusivity can cause the matrix to remain pressurized longer than the fractures, resulting in displacement that persists longer than would be expected based on well bore pressure alone.

4. The hydromechanical response in sedimentary rocks could be explained using poro-elastic analyses involving interactions between multiple fractures and matrix.

5. It is feasible to measure high resolution tilt signals with a removable tiltmeter deployed temporarily in a well.

2010

1. Portable borehole tiltmeter can be mobilized and deployed at remote locations.

2. Feasible to make downhole tilt measurements during pumping tests.

3. Tilt signals during a field test in fractured rock in Virginia indicate that tilting on the order of microradians occurs in the up-dip direction. This magnitude and direction of tilting is consistent with theoretical simulations.

4. The magnitude of tilting decreased with consecutive pumping tests as a site where a hydraulic fracture had been recently created. A possible explanation is the pumping tests cause seating of the asperities on the fracture surface. This process is consistent with conceptual models, but has not been described in the field due to limitations in instrumentation.

5. A portable device for measuring both tilt and extension has been successfully demonstrated during pumping tests. The device gives resolution of +/- 5 nm of extension and +/- 30nrad of tilt.

6. Theoretical analyses of combined tilt and deformation during pumping tests have been developed to identify important characteristics of the hydromechanical signal.

2011

1. An analytical solution, numerical calculations and field data show that storage characteristics of an idealized fractured aquifer change with both space and time during transient well tests.

2. The volume of water released from storage per unit head drop per volume of a fracture, the normalized storage, increases with time during pumping, but it drops suddenly and may become negative at the beginning of recovery.

3. Profiles of normalized storage generally increase with radial distance along a fracture, but they are marked by a sharp increase and a sharp decrease at the leading edge of the region affected by the wellbore pressure transient.

4. The responses can be explained conceptually because storage changes in fractures depend not only on changes in local fluid pressure, but also on fluid pressure integrated over the fracture face.

5. These findings show that normalized storage is a non-local response to hydraulic transients. The definition of specific storage is identical to that of normalized storage, except specific storage is generally regarded as an aquifer property.

6. Our findings suggest that the use of specific storage as an aquifer property may misrepresent the process affecting change of storage during hydraulic transients in fractured rock, or thin sedimentary aquifers.

2012

1. A new extensometer capable of measuring deformation in 3D was developed and demonstrated.

2. Field applications under ambient conditions shows that fractures deform in response to barometric fluctuations.

3. Dipping fractures cause a distinctive tilt pattern that can be seen in field data.

4. A new closed form analytical solution was derived describing the deformation in the vicinity of a well test.

Training and Development:

Mr. Xiaoyu Song completed his M.S. degree in 2010.

Outreach Activities:

Journal Publications

Germanovich, L. N., and Murdoch, L.C., "Injection of Solids to Lift Ground Surface in Coastal Areas", Proceedings of the Royal Society A: Mathematical, Physical, and Engineering Sciences, p. 3225, vol. 466, (2009). Published, 10.1098/rspa.2010.0033.

L.C. Murdoch and L.N. Germanovich, "Storage characteristics as a non-local response of fractured rock aquifers to well tests", Water Resources Research, p. , vol. , (2012). Submitted,

Trever Slack, L.C. Murdoch, L.N. Germanovich. D. Hisz, "Reverse Water Level Response During Interference Slug Tests in Fractured Rock", Journal of Hydrology, p. , vol. , (2012). Submitted,

D. Hisz, L.C. Murdoch. L.N. Germanovich, "A Portable Borehole Extensometer and Tiltmeter for Characterizing Aquifers", Water Resources Research, p. , vol. , (2012). Published,

Books or Other One-time Publications

Murdoch, L.C., T. Schwesinger,
L.N. Germanovich, "Interpreting Mechanical Displacements During Hydromechanical Well Tests in Fractured Rock", (2006). Abstract, Published
Bibliography: Eos Trans. AGU, 87(52)

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Hisz, D B, Ebenhack, J., Burbey, T J, Germanovich, L N, Murdoch, L C., "Multi-Component Deformation of a Dipping Fracture Zone during a Well Test", (   ). Book, Abstract
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Murdoch, L.C., D.B. Hisz, J.F. Ebenhack, D.E. Fowler, C. R. Tiedeman, L. N. Germanovich, "Analysis of Hydromechanical Well Tests in Fractured Sedimentary Rock at the NAWC Site, New Jersey", (2009). Book, Published
Bibliography: Asheville 2009, the 43rd US Rock Mechanics Symposium and 4th U.S.-Canada Rock Mechanics Symposium, held in Asheville, NC June 28th ? July 1, 2009, 8 p.

Murdoch, L.C., D.B. Hisz, J.F. Ebenhack, D.E. Fowler, C. R. Tiedeman, L. N. Germanovich, "Analysis of Hydromechanical Well Tests in Fractured Sedimentary Rock at the NAWC Site, New Jersey", (2009). Book, Published
Bibliography: Asheville 2009, the 43rd US Rock Mechanics Symposium and 4th U.S.-Canada Rock Mechanics Symposium, held in Asheville, NC June 28th ? July 1, 2009, 8 p.

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

This project has contributed to the understanding of fundamental aquifer mechanics by developing innovative instrumentation, theoretical analyses and field techniques.

1. Specific storage is regarded as a material property in conventional groundwater hydrology, but the project generated field and theoretical evidence showing that it varies with both space and time during a well test. This finding shows that storage change is a variable response that cannot be characterized by the material property specific storage.

2. Matrix deformation. Injection causes fractures to dilate, but the matrix adjacent to the fractures is compressed. This occurs as a response to the loading within the fracture. This effect had never been described, to our knowledge.

3. Reverse water level fluctuations. Fluid pressures increase in much of a fracture during injection, but they decrease at the leading edge of the zone affected by the well. This occurs because the dilation of the fracture walls occurs beyond the leading edge of the pressure front created by injection. This effect is related to the reverse water level responses known as the Noordbergum and Rhade effects, but it differs fundamentally from those known responses because it occurs within a hydraulically active fracture instead of within a confining unit. This effect has never been documented or explained.

4. Integrated aquifer characterization. Data from hydromechanical well tests can be integrated with water level changes due to barometric effects and Earth tides to characterize fractured rock aquifers. This approach appears to give more reliable results than conventional methods. Application of these techniques at a well that was hydraulically fractured shows that the compliance of the fracture decreases with each pumping test, presumably because asperities on the fracture face slip slightly and become better seated during each test.

5. Dipping fracture zones. Deformation that occurs during pumping can be characterized with both extensometers and tiltmeters. Tiltmeters allow rigid body rotation to be measured, whereas this effect cannot be detected by extensometers. Tilt signals can be interpreted using theoretical analyses to improve estimates of permeability distribution. An example field test conducted at the collaborator's site in Clemson shows a response that can be explained by an underlying fracture zone that is inclined, and the results of the test can be interpreted to yield the orientation of the fracture zone. Future applications of combined tiltmeters and extensometers will enable improved estimates of the structure of fracture zones.

6. Instrumentation was created for this project to measure displacements of aquifer materials on the scale of nanometers, which is one to two orders of magnitude smaller than was capable with earlier portable devices. This will allow effects to be measured that were previously invisible, opening a variety of opportunities in hydrology.

Contributions to Other Disciplines:

Insights into aquifer characterization and well performance resulting from hydromechanical effects outlined for aquifers will also be relevant to wells used in other disciplines. As a result, the findings of this project will contribute to petroleum engineering, geothermal energy recovery, mining, among other fields.

We have recently developed a compact device for measuring deformation in 3D. This devices was developed for downhole tools to be used during well testing, but it would be equally applicable in a range of applications related to structural health monitoring, geotechnical engineering, mining, energy recovery, etc.

The combination of displacement and pressure measurements appears to have the capability to improve understanding of aquifer characteristics. This may have particularly important applications in understanding effects of CO2 sequestration.

This project has inspired a new idea for protecting low lying areas against flood damage. The idea is to inject sediment into the subsurface, thereby lifting the ground surface potentially high enough to reduce flood damage.

This project is focused on characterizing very small displacements when water is injected into a well, and the new idea is to create large displacements by injecting water and sediment. As a result, the new idea was inspired by the current project, although it is a step beyond the objectives of this project. A paper describing this idea was recently published. This idea could contribute to public welfare because it has the potential to be an alternative way to protect coastal infrastructure from flooding.

As a part of this project, a downhole system that can be deployed in submerged setting has been designed and fabricated. This required potting electronics in waterproof materials and enclosures, and for making reliable electrical connections in submerged conditions. A broader impact of this work is an ongoing development of the flow measurement apparatus that was deployed on the ocean floor at the Endeavour Segment of the Juan de Fuca Ridge using submersible Alvin (under separate funding).

Contributions to Human Resource Development:

Xiaoyu Song graduated with M.S. degree.

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

The project has contributed to the development of a proposed method for raising ground elevations by injecting fluid and solids into wells. This technique could advance public welfare by raising elevations in coastal areas and protecting them from catastrophic flooding. This application is described in a recently published paper http://rspa.royalsocietypublishing.org/content/early/2010/05/27/rspa.2010.0033.short?rss=1.

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